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Reduced-order observer for real-time implementation speed sensorless control of induction using RT-LAB software

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ABSTRACT

In this paper, Reduced-Order Observer For Real-Time Implementation Speed Sensorless Control of Induction Using RT-LAB Softwareis presented. Speed estimation is performed through a reduced-order observer. The stability of the proposed observer is proved based on Lyapunov's theorem. The model is initially built offline using Matlab/Simulink and implemented in real-time environment using RT-LAB package and an OP5600 digital simulator. RT-LAB configuration has two main subsystems master and console subsystems. These two subsystems were coordinated to achieve the real-time simulation. In order to verify the feasibility and effectiveness of proposed method, experimental results are presented over a wide speed range, including zero speed.

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1. INTRODUCTION

In power electronics control of AC machine drives many methods employed of control in various high performance industrial applications [1]. This has been conventionally achieved by using DC motors with their simple control structure. AC machines are generally inexpensive, compact and robust with low maintenance requirements compared to DC machines but require complex control [2].

High performance scalar control of induction motor method require speed or position information for its operation. Generally speed or position transducers provide this information. However these mechanical sensors are costly and fragile. On the other hand, sensorless drives operating without speed or position transducers have the advantage of reduced hardware complexity and lower cost, reduced size of the drive machine, elimination of the sensor cable, better noise immunity, increased reliability, and less maintenance requirements [3]. Due to these reasons speed sensorless systems, in which rotor speed measurements are not available, are preferred and find applications in many areas for speed regulation, load torque rejection and speed tracking purposes.

Estimation of unmeasurable state variables is commonly called observation. A device (or a computer program) that estimates or observes the states is called a state-observer or simply an observer. If the state-observer observes all state variables of the system, regardless of whether some state variables are available for direct measurement, it is called a full-order state-observer. An observer that estimates fewer than the dimension of the state-vector is called reduced-order state-observer or simply a reduced-order observer. If the order of the reduced-order state-observer is the minimum possible, the observer is called minimum-order state-observer [4].

Many researchers have focused on the design of sensorless control algorithms for induction motor. Reduced-order observer is used for speed estimation, one of its disadvantages is the sensitivity to parameter variation especially at low speed or under load application. Various methodologies have been exploited for speed estimation: Adaptive Observers [5], Sliding Mode Technique [6], Extended Kalman Filter [7], MRAS observers [8]. Figure 1 shows a chart of the different speed sensorless estimation strategies:

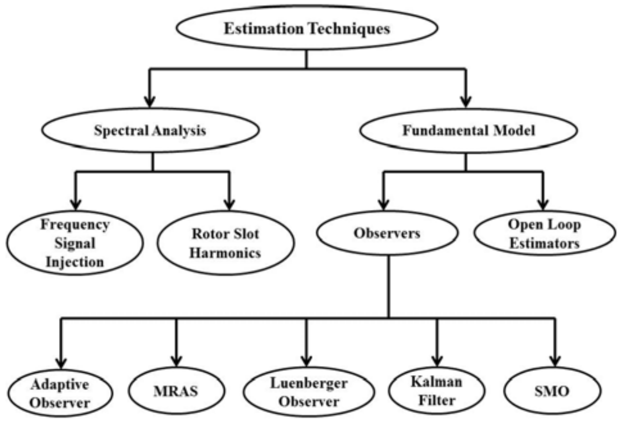


Figure 1. Speed sensorless estimation strategies

The problem of sensorless controlled induction motor related to the stability of the control method. This is usually faced with direct field oriented control and direct torque control strategies, combined with speed-flux observer. The aim of this paper is to test a reduced order observer for speed sensorless control of IM and its stability over a wide speed range. For the detailed stability analysis the reader could refer to [9-12].

In this research paper, reduced-order observer for speed sensorless scalar control of induction motor has been designed and implemented in real-time using RT-LAB package. The proposed observer estimates the rotor speed, the stator currents. For developing the sensorless control algorithm, modeling of induction motor is presented. Lyapunov's stability criterion is employed to estimate rotor speed. The experimental results show the effectiveness of the proposed sensorless control method based on a reduced-order observer.

2. INDUCTION MOTOR MODEL

The dynamic model of induction motor in stationary reference frame α, β may be written as given [13-15]:

$$\begin{cases} \dfrac{di_{s\alpha}}{dt} = -\dfrac{1}{\sigma L_s}\left(R_s + \left(\dfrac{L_m}{L_r}\right)^2 . R_r\right) i_{s\alpha} + \dfrac{L_m . R_r}{\sigma L_s L_r^2}\varphi_{r\alpha} + \dfrac{Lm}{\sigma L_s Lr} wr.\phi_{r\beta} + \dfrac{1}{\sigma L_s} Vs\alpha \\ \dfrac{di_{s\beta}}{dt} = -\dfrac{1}{\sigma L_s}\left(R_s + \left(\dfrac{L_m}{L_r}\right)^2 . R_r\right) i_{s\beta} - \dfrac{Lm}{\sigma L_s Lr} wr.\phi_{r\alpha} + \dfrac{L_m . R_r}{\sigma L_s L_r^2}\varphi_{r\beta} + \dfrac{1}{\sigma L_s} Vs\beta \\ \dfrac{d\varphi_{r\alpha}}{dt} = \dfrac{L_m . R_r}{L_r} is\alpha - \dfrac{R_r}{L_r}\varphi_{r\alpha} - wr.\varphi_{r\beta} \\ \dfrac{d\varphi_{r\beta}}{dt} = \dfrac{L_m . R_r}{L_r} is\beta + wr.\phi_{r\alpha} - \dfrac{R_r}{L_r}\varphi_{r\beta} \end{cases} \quad (1)$$

where :

L_m, L_r, L_s are magnetizing, rotor self-leakage and stator self-leakage inductances, R_r, R_s are rotor and stator resistances, σ is leakage coefficient $\sigma = 1 - \frac{L_m^2}{L_r . L_s}$,

The electromagnetic torque can be expressed by:

$$T_e = \frac{3.P.Lm}{2.Lr}.(\varphi_{r\alpha}.i_{s\beta} - \varphi_{r\beta}.i_{s\alpha}) \tag{2}$$

3. DESIGN OF REDUCED-ORDER OBSERVER

In this paper the rotor speed and the stator currents $\hat{i}_{s\alpha}$, $\hat{i}_{s\beta}$ were estimated using reduced-order observer, the state equation of the induction machine is given as follows:

$$\dot{\hat{X}} = A\hat{X} + BU + K(Y - \hat{Y}) \tag{3}$$

$$A = \begin{bmatrix} \frac{-1}{Tr} & -\hat{w} \\ \hat{w} & \frac{-1}{Tr} \end{bmatrix}; \quad B = \begin{bmatrix} \frac{L_m}{Tr} & 0 \\ 0 & \frac{L_m}{Tr} \end{bmatrix}; \quad K = \begin{bmatrix} k1 & k2 \\ -k2 & k1 \end{bmatrix}$$

where A is the estimated value and K is the observer gain matrix with :

$$\hat{X} = \begin{bmatrix} \hat{\phi}_{r\alpha} \\ \hat{\phi}_{r\beta} \end{bmatrix} \quad Y = \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} \quad U = \begin{bmatrix} V_{s\alpha} \\ V_{s\beta} \end{bmatrix} \quad \hat{Y} = \begin{bmatrix} \hat{i}_{s\alpha} \\ \hat{i}_{s\beta} \end{bmatrix}$$

The estimation error can be expressed as follows:

$$\hat{e} = (A + KB)e + \Delta A[\phi_{r\alpha} \quad \phi r\beta]^T \tag{4}$$
$$e = \begin{bmatrix} e_{\phi_{r\alpha}} & e_{\phi_{r\beta}} \end{bmatrix}^T$$

where

$\Delta A = \hat{A} - A$

The following Lyapunov function is defined:

$$V = e^T.e + l.(\hat{w} - w)^2 \tag{5}$$

where l is a positive constant.

The observer gain matrix K is chosen such that the derivative of a positive definite Lyapunov function V becomes negative definite as explained in [16].

The rotor speed of induction motor can be estimated by PI controller:

$$\hat{w} = \left(Kp + \frac{Ki}{s}\right) * \left(e_{\phi_{r\beta}}\hat{\phi}_{r\alpha} - e_{\phi_{r\alpha}}\hat{\phi}_{r\beta}\right) \tag{6}$$

where Kp and Ki are the proportional and integral constants, respectively. The block diagram of speed estimation of induction motor can be considered as shown in Figure 2.

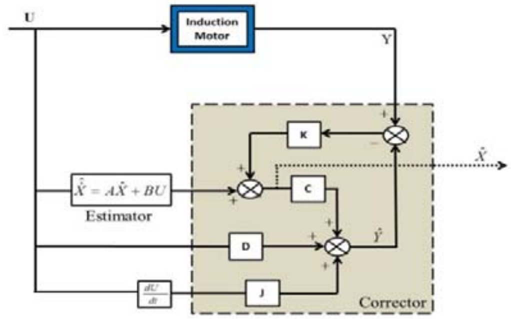


Figure 2. Block diagram of reduced-order observer

4. SCALAR CONTROL SCHEME

Due to its simplicity, scalar control is one of the most commonly used methods in industry machine drives. However, its dynamic performance is limited, even in closed loop, particularly when operating in regions of low speed [17].

The essence of control to maintain a constant scalar Voltage/Frequency ration (V/f) in order to maintain the magnetic flux in air-gap constant at maximum value. If the voltage does not have a proper relationship with the frequency. The machine can operate in the saturation or field weakening region [18]. The electromagnetic flux produced can be calculated by using the relationship between the voltage and electromagnetic flux, expressed as:

$$Vs = \omega s * \phi s * \sqrt{\frac{\left(\frac{Rs}{\omega s.Ls} - \omega r.Tr.\sigma\right)^2 + \left(1 + \left(\omega r.Tr.\frac{Rs}{\omega s.Ls}\right)\right)^2}{1 + (\omega r.Tr.\sigma)^2}} \tag{7}$$

Closed loop control of the speed of an AC induction motor can be implementaed based on the constant Voltage/Frequency ration (V/f) principle [19].

Indeed, in practice, we are usually satisfied with a simplified control law, corresponding to the negligence of the ohmic drop (Rs= 0) in (22), to give us:

$$Vs = \omega s * \phi s \tag{8}$$

Hence the relationship voltage and frequency, by maintaining the constant stator flux. The principal scheme of speed sensorless control of induction motor based on a reduced-order observer is shown in Figure3.

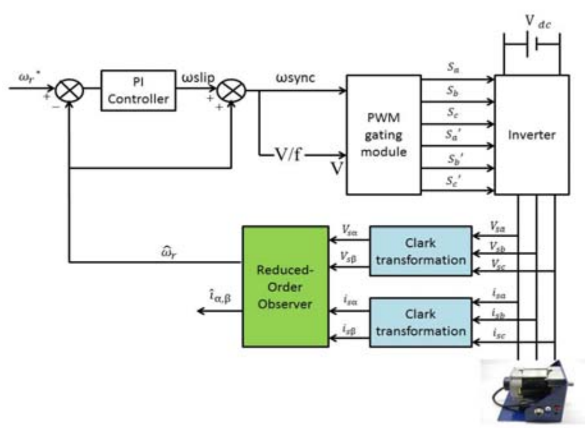


Figure 3. Block diagram of speed sensorless control of induction motor based on a reduced-order observer.

5. DESCRIPTION OF REAL-TIME SIMULATION AND SETUP LABORATORY

The simulation of sensorless control algorithm is executed on OP5600 real-time digital simulator using one of a dual quad-core computer. Table 1, Summarizes the characteristics of the RT-LAB system used in this research paper.

Table 1. RT-LAB simulator characteristics

Items	Quantity	Description
Operating system	1	Redhat
Chassis	1	OP5600 Chaissis (OP5142)
CPU	1	1*(4 cores 2.4 GHZ)
Memory	1	4GB
Motherboard	1	X8DTL-I-O
OP5340 Ain	1	16Ch
OP5330 Aout	1	16Ch
OP5353 Din	1	32Ch
OP5354 Dout	1	32Ch

RT-LAB simulator also is equipped with Xilinx Spartan 3 programmable FPGA card. The FPGA card can be programmed with Xilinx system generator blockset for Simulink enabling implementation of complex sensor models like resolvers or even complex motor drives [20, 21].

The development process of the integrated Simulink model include following steps:

-Construct block diagram models of the integrated sensorless control algorithm utilize Matlab/Simulink, and then verify feasibility of the algorithm through offline simulation.

-Covert Simulink models into RT-LAB compatible models, based on RT-LAB model design specification.

- Use (RTW) and model separation to generate real-time C code, and uploaded the C code into OP5600 digital simulator to perform real-time simulation.

- Executing the model by launching the real-time Simulation on all the nodes (parallel execution).

The RT-LAB platform is composed of one host PC and one real-time target computer as shown in Figure 4. The network connection TCP/IP protocol is used for communication between computers; the host PC controls simulation through RT-LAB console subsystem. The master subsystem model of sensorless control algorithm is converted into C code using Matlab real-time Workshop (RTW) facility, this generated C code is downloaded to target computer via Ethernet link [22]. Subsystem console runs in the host PC used to display the real-time sensorless control algorithm results.

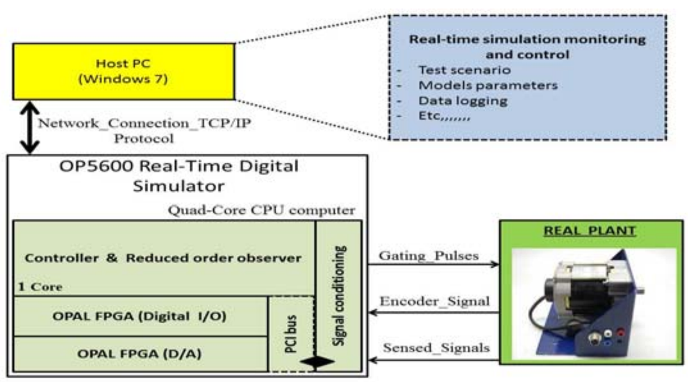


Figure 4. Structure of the RT-LAB simulator with the attached real-plant.

The experimental setup of the real-time sensorless control of induction motor based on a reduced order observer is shown in Figure 5. The experimental test has been carried out to verify the effectiveness of the proposed reduced order observer, a 3-ph induction motor fed by a three phase Drivelab Board inverter is chosen. The switching frequency was set at 19kHz, while the time-step was fixed to 100µs.

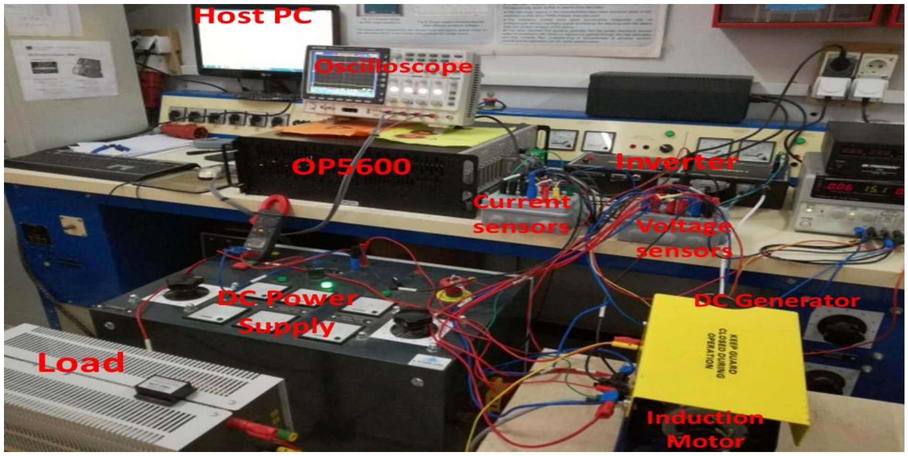
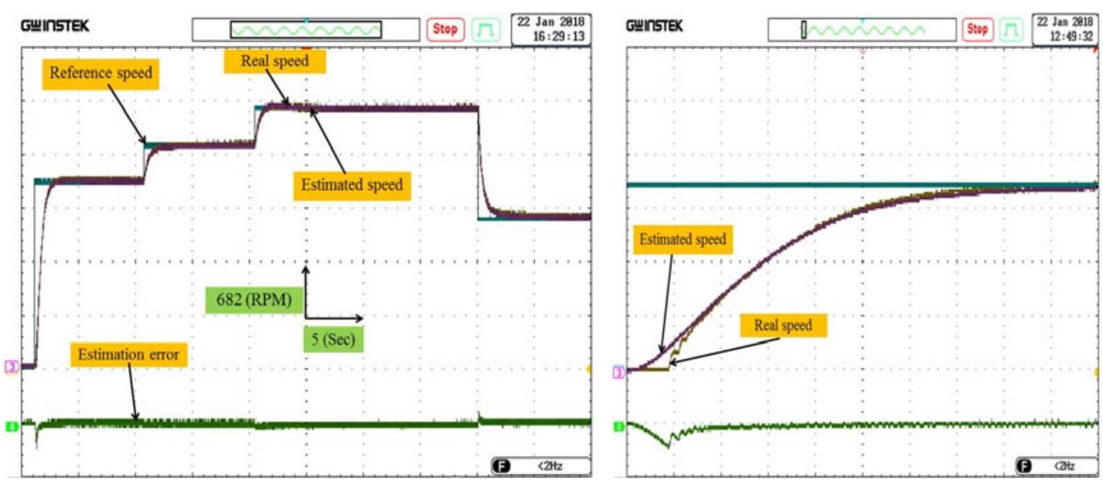


Figure 5. Experimental setup of RT-LAB platform at CAOSEE Laboratory.

6. EXPERIMENTAL RESULTS

The real-time implimentation of reduced-order observer results, have been obtained by using GW-Instek numerical oscilloscope wich was linked with the real-time analog outputs interfaces. Figure 6(a) depicts the actual motor speed and the estimated speed, while Figure 6(b) shows the zoomed version of Figure 6(a).

It can be noticed that the estimated speed follows the real speed at different points of speed range (2388, 2866, 3344, 1910rpm) the estimation error converges to zero. It's clear that the drive system works at a wide range of speeds, to reveal the effectiveness of the proposed reduced order observer four steps change applied to speed reference, the model was compiled and excuted with sampling time of 50 µs on OP5600 real-time digital simulator, the operation with change in reference speed is the main focus of this paper and the great challenge for estimation algorithms designed for the speed-sensorless control of induction motors. Figure 6(a) indicates the good tracking characteristics and more effectiveness, the estimated speed always followed the reference. The step change of the reference speed doesn't affect the performance of the system. The advantage of this work in that the reduced order observer is simple to implemente in real-time and doesn't contain complexe calculations and has good performances compared to another full order observers that requires more calculation time and not easy to implement those full order observer in real-time.



(a) (b)

Figure 6. Speed curves, (a) The reference, actual and estimated speed with estimation error, (b) Zoomed version of (a)

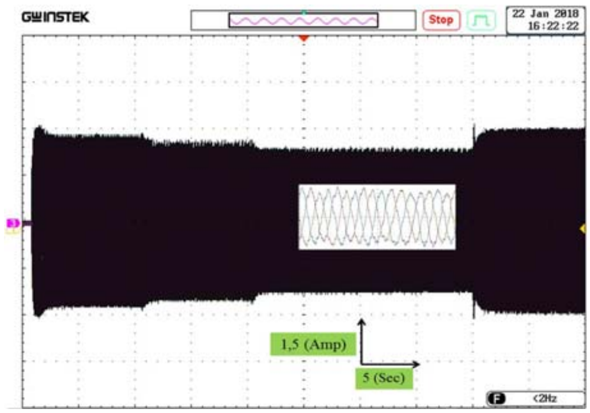


Figure 7. Stator currents: isa, isb, isc [A]

As shown in Figure 8 the estimated stator current components converge to the real stator current components with small phase shift, it's clear that the waveforms of currents are sinusoid.

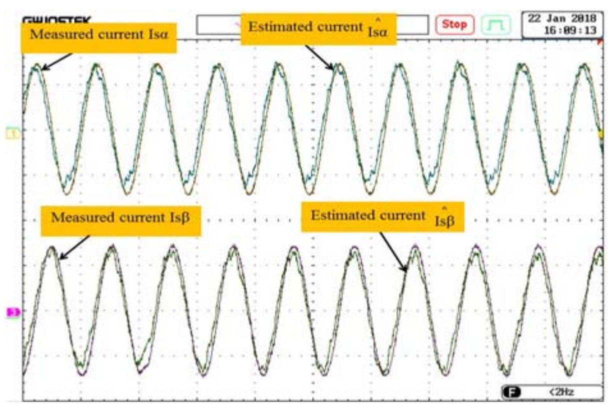


Figure 8. Real and estimated components of stator current in the fixed frame (α,β)

From the above experimental results we concluded that that the sensorless control scheme associated with reduced-order observer has a fast response time and good estimation accuracy over a wide speed range.

7. CONCLUSION

In this paper, a reduced-order observer for speed sensorless sacalar control of induction motor is presented and implemented in real-time. The drive system with the proposed observer is built offline using Matlab/Simulink blocksets and executed in real-time using RT-LAB package and an OP5600 target. Digital simulations and experimental setup have been carried out in order to validate the proposed sensorless diagram. The experimental results show that the drive system works at a wide range of speeds, this indicates the good accuracy and robustness of the designed observer.

APPENDIX INDUCTION MOTOR PARAMETERS

The parameters of the three-phase Induction motor, employed for real-time implementation, in SI units are: 120W, 133Hz, P=2, Rs=1.05 ohm, Rr=1.705 ohm, Ls=0.02939 H, Lr=0.02939 H, Lm=0.02526 H, J=0.00037 Kg.m^2, fr=0.00006 SI.

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